

Total petroleum Hydrocarbons in Dissolved, Particulate water, and Sediment in Shatt Al-Arab Estuary and Iraqi Coastal Environment

Haider K. Haider¹ , Salah M. Salah¹ , Hamid T. Al-Saad² 

¹Applied marine science, College of Marine Sciences, University of Basrah, Basrah, Iraq

²Natural marine sciences, College of Marine Sciences, University of Basrah, Basrah, Iraq

Corresponding Author E-mail: haider.kadimm@uobasrah.edu.iq

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Abstract

In this research, there is a comprehensive analysis regarding the total Hydrocarbons (THPs) in the Shatt Al-Arab estuary and the, Iraqi coastal water of northwestern Arabian Gulf over the course of the year 2025. Each of the three environmental compartments (dissolved phase, suspended solids, and the sediment) were evaluated as a means to view hydrocarbon concentrations found in these three compartments. The findings have shown that there was a clear and systematic partitioning (or distribution) of THPs between the environmental compartments that were studied. The dissolved components contained a relatively low concentration of hydrocarbons (0.096 to 0.160 $\mu\text{g}/\text{l}$), which was somewhat of a predictable pattern given the limited solubility of petroleum hydrocarbons as well as the rapid loss of dissolved hydrocarbons from the water column into sediment. Conversely, suspended particulates acted as a transitional transport medium between dissolved and bottom sediments and had hydrocarbon concentrations ranging from a maximum of 39.41 $\mu\text{g}/\text{g}$ (Station 3) which was influenced by resuspension processes and hydrodynamic activity. The bottom sediments act as the main and most stable deposition site for hydrocarbons, with hydrocarbon concentrations ranging from 46.13-92.41 $\mu\text{g}/\text{g}$ with the greatest accumulation of hydrocarbons at Station 1 and suggesting that the hydrocarbons have remained persistent over time and are from anthropogenic input. The statistical evaluations performed by the one-way ANOVA and Tukey's HSD test demonstrated a statistically significant amount of spatial variability ($p < 0.001$), specifically indicating spatially recognized estimation pollution hotspots with localized sources and sediment characteristics. In general, this research work will provide the baseline data for further research and outlines the need for multiple-sector strategies. We recommend the assessment of ecological health to monitor possible bioaccumulation risks to ensure the future environmental security of the Shatt Al-Arab and the communities that depend on the water resources within it.

Keywords: Total Hydrocarbon, Dissolved Phase, Particulate Matter, Sediment, Shatt Al-Arab Estuary, Iraqi Coastal Environment.



Introduction

As an indicator of oil contamination in oceans, total hydrocarbons (THC) are a large group of organic materials created through both natural (biogenic) and human means. Hydrocarbons occur in three areas of coastal and estuarine environments: in the dissolved phase (water), in the particulate or solid phase (suspended and settled), and in the bottom sediments (or solids that have settled out of suspension). Each phase records a different method of transportation, different physical and chemical behaviours, and receives different signatures from the source of the hydrocarbon. Therefore, knowledge of how THC are distributed amongst the three phases is a critical part of evaluating the extent of contamination, identifying major sources, and conducting an assessment of the potential for ecological damage from the source of the emissions (Al-Hejuje *et al.*, 2018; Zambrano-Anchundia *et al.*, 2026).

The area of the Shatt Al-Arab Estuary and the surrounding coastal region of Iraq (northwest Arabian Gulf) is one of the most hydrocarbon contaminated marine areas of the world. There are extensive long-term oil exploration, development, transportation, refining, shipping, and other petroleum activities in the region. In addition, the Tigris, Euphrates, and Karun rivers flow into the Shatt Al-Arab with substantial amounts of oil contamination, resulting in a very complex system of hydrocarbons (petrogenic, pyrogenic, and biogenic), which create a very sensitive and dynamic ecological system (Al-Saad *et al.*, 2018).

The Shatt Al-Arab Estuary is the main pathway in which terrestrial organic substances and hydrocarbon pollutants enter into the north-west region of the Arabian Gulf from land-based sources (Galo *et al.*, 2022). Most of the hydrocarbon contamination in the estuarine water column comes from urban/industrial wastewater discharges from large urban centers (i.e., Basrah, Abadan), agricultural runoff from the vast river watershed, and continuous discharge of oil from oil fields, pipelines and refineries. Hydrocarbons emitted due to human activities (marine discharge from operational spills) and hydrocarbon deposition from atmosphere due to flaring of gas or industrial emissions, contributes to the total input of hydrocarbons into the Shatt Al-Arab River and its coastal environment (Nadim *et al.*, 2008; Ediagbonya *et al.*, 2025).

Both low molecular weight aliphatic and water-soluble aromatic hydrocarbons dominate the dissolved fraction of hydrocarbons in the water column and, therefore, readily move along with river flow through the estuary. High concentrations of dissolved total hydrocarbons (THCs) in the Shatt Al-Arab River often coincide with increased river discharge of freshwater and lower levels of salinity, which enhances the transport and bioavailability of THCs and subsequently increases the ecological toxicity potential of THCs (Salem *et al.*, 2022). Particulate hydrocarbons are primarily associated with suspended particulate matter and consist mainly of high molecular weight derivatives of petroleum and weathered oil. The particulate hydrocarbon fraction is generated by dissolved hydrocarbon adsorbing to solids; resuspension of contaminated sediments;

river transport of fine grained material; and emissions of shipping activities (Al-Hejuje *et al.*, 2020).

In the Shatt Al-Arab Delta and Iraqi coast, sediments are the final repository of hydrocarbons. Sedimentary THCs represent the cumulative effect of the hydrocarbon input provided by both the water column and by the direct deposition from oil spills and industrial discharge over time. Many studies show that THPs are generally found to be most concentrated in fine, organic-rich sediments because of the combination of strong sorption processes with slower rates of degradation promote HC preservation (Al-Saad *et al.*, 2016). Factors including grain size distribution; total organic carbon; redox conditions; and proximity to pollution sources exert significant controls over sedimentary hydrocarbon distributions (Hashim., 2025).

Beyond the estuary, the influence of the Shatt Al-Arab plume on the north-west Arabian Gulf results in the dispersal of riverborne hydrocarbons over a wide coastal area and is influenced by seasonal patterns of discharge and general circulation across the region. THPs in offshore and nearshore waters of the Gulf are primarily attributed to petroleum related activities (Younus and Younis., 2023), which include produced water discharges from the offshore platforms chronic operational releases and inputs from large oil terminals and refineries. The long-term pollution of Gulf sediments with hydrocarbons is largely a result of the legacy of large scale oil spills (Gulf War oil spill 1991) and continuing smaller scale releases (Literathy *et al.*, 2002; Al-Imarah *et al.*, 2023).

The spatial distribution of THPs in the dissolved, particulate and sediment phases of the Shatt Al-Arab Estuary and the Iraqi coastline reflect the effects of riverine transport, oil-related activities and atmospheric deposition and hydrodynamic processes working together over time. The THPs in the sediments represent an historical record of these contaminant inputs. The THPs in the dissolved and Particulate fractions indicate that there are currently and have been sources of hydrocarbons to the environment. Continuously monitoring and accurately determining the sources of hydrocarbons (source apportionment) will therefore be important for the effective management of the environment and for assessing risks in the northwest Arabian Gulf (Massoud *et al.*, 2011).

Eyond the technical quantification of TPH, this study acknowledges that the Shatt Al-Arab is more than a waterway; it is a vital life-support system for the region (Galo *et al.*, 2022). Therefore, linking these contamination levels to potential ecological and human health risks is not merely a scientific task, but a necessary step toward safeguarding the environmental heritage and the livelihoods of the coastal communities in Southern Iraq.

Materials and Methods

water and sediment (bottom) samples were taken, in 2025, from Shatt Al-Arab Estuary and the Iraqi coastline (located in the north-western Arabian Gulf) (shown in Fig 1) Fieldwork and sampling procedures were conducted under official authorizations from the relevant security and environmental authorities. Necessary security clearances and sampling permits were obtained from the Iraqi Naval Forces Command and the Fourth

Region Border Guard Command (Fourth District) to ensure legal access to the study sites and compliance with national safety and environmental protocols. To measure the total hydrocarbons (THPs) content. THPs measurements were performed using methods established and accepted by many international scientific organizations for use in marine studies, specifically using spectro-fluorometric methods after extracting the hydrocarbons from water and sediment using solvents and liquid-liquid extraction with n-hexane for water samples and Soxhlet extraction with a mixture of n-hexane/dichloromethane for sediment samples following already established methods (UNEP., 1992).

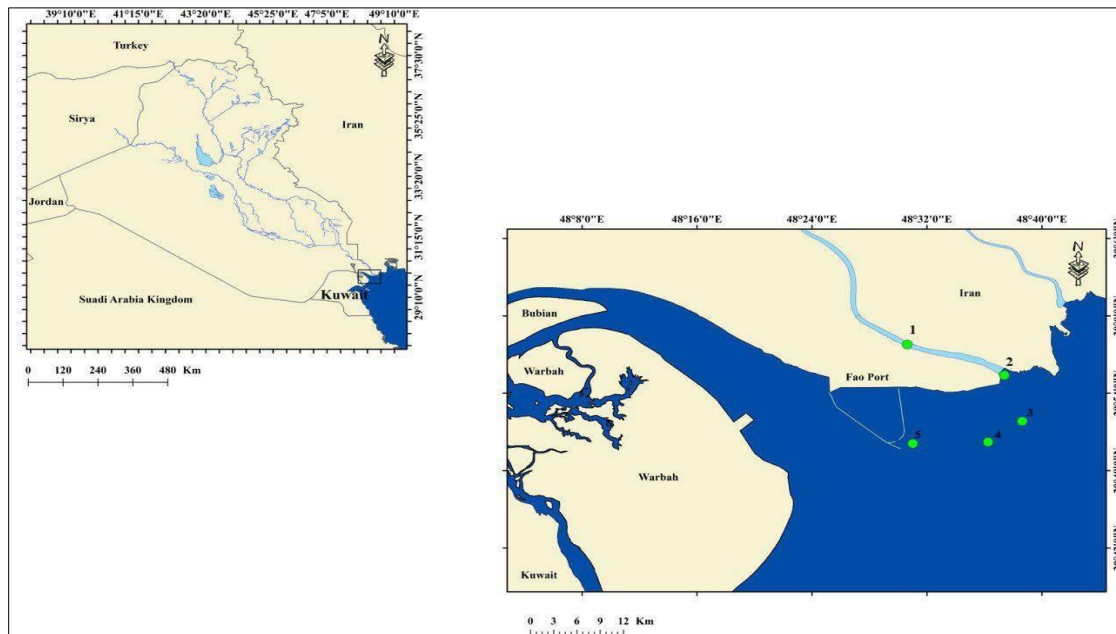


Figure (1): Study sites.

Both water (collected in opaque glass bottles) and sediment (0-5 cm layer; collected using a grab sampler) samples were maintained at 4°C before analysis to minimize degradation of hydrocarbons. After extracting hydrocarbons from water samples, the extracts were dried over anhydrous sodium sulfate (to remove residual water/moisture) and then concentrated to a final known volume under reduced pressure using a rotary evaporator. Since matrix interferences can cause inaccuracies in testing, concentrated extracts were purified by silica gel column chromatography prior to instrumental analysis. Spectro-fluorometry was used to identify and quantify hydrocarbon compounds, and the total hydrocarbon content (THPs) for each sample was calculated as the combined concentration of hydrocarbon compounds per sample and expressed as either µg/l for water samples or as µg/g dry weight for sediment samples. This provided a composite measure of petroleum hydrocarbon contamination that allowed for spatial comparison with previous studies. To ensure the highest level of scientific integrity and data transparency, the analytical method was rigorously validated. Instrument calibration was performed using a five-point standard curve, achieving excellent linearity with a correlation coefficient of $R^2 > 0.998$. The Limit of Detection (LOD) and Limit of

Quantification (LOQ) were determined based on signal-to-noise (S/N) ratios of 3 and 10, respectively. The LOD ranged from 0.01 to 0.05 µg/L, while LOQ values ranged from 0.03 to 0.15 µg/L, depending on the specific hydrocarbon compound.

All samples—across the dissolved, particulate, and sediment phases—were analyzed in triplicates, and the mean values were reported to minimize analytical variance. Procedural blanks were processed alongside every batch to monitor for laboratory contamination, while Certified Reference Materials (CRMs) were utilized to calibrate the instruments and verify the accuracy of the quantification.

Results and Discussion

Dissolved Phase

The assessment of petroleum contamination in this study focuses on Total Petroleum Hydrocarbons (TPH) across three distinct phases: dissolved, particulate, and sediment. Although the analytical method (spectro-fluorometry) does not differentiate between specific classes like PAHs or alkanes, it serves as a highly sensitive screening tool to evaluate the overall distribution of petroleum across these three compartments. This comprehensive approach provides a vital baseline for understanding the partitioning of pollutants in the Shatt Al-Arab environment (Kareem *et al.*, 2023).

Values of hydrocarbon concentrations for dissolved phases are also shown in Table (1). Many of the measured concentrations in the dissolved phase of the target study were found to be less than those of other measurable phases. The average concentration of hydrocarbon material was measured to be between .096 and 160 µg/l. The individual measured sites had different values for their concentrations as well: ST1 had the highest measurement at .160 µg/l; then ST3 had the 2 highest measurement at .135 µg/l; ST5 had a 3rd highest measurement of .113 µg/l; ST2 had the 4th highest at .107 µg/l; and ST4 had the lowest at only .096 µg/l. The hydrocarbon material dissolved in the water showed evidence of reducing amounts of this type of material from one measured location to the next thus showing behaviors related to the movement of dissolved hydrocarbons throughout the water system of the environments shown in Figure (2).

Dissolved hydrocarbons may be reduced over time due to the overall physicochemical properties of total hydrocarbons (THPs). The hydrophobic nature of these hydrocarbons results in low solubility with respect to water, causing these compounds either to adsorb to suspended particulates or to be deposited in bottom sediment rather than remaining in solution (Al-Saad *et al.*, 2018). Furthermore, dissolved hydrocarbons can also be reduced over time due to the influences of other physical processes (dilution, photodegradation, and/or microbial degradation) (Al-Imarah *et al.*, 2010; Al-Atbee *et al.*, 2024). In contrast, the high concentration observed at station ST1 (as illustrated in Fig. 2) is a strong indication that fresh or continuous inputs of hydrocarbons to this area may originate from local human activities or surface runoff. These types of inputs occur before hydrocarbons have had a chance to partition and redistribute among various phases throughout the study area.

The statistical significance of how dissolved-phase hydrocarbons are spatially distributed has been confirmed by the results of the One-Way ANOVA analysis. The F-value (389.22, $P < 0.001$) suggests that the variation seen between the stations is not an artefact of chance and instead reflects a continuous gradient of contamination. The location of the peak at ST1 (illustrated in Figure 2) serves as a statistical reference for recent anthropogenic inputs. The comparable values of experimental data between the two figures also support the precision of the sampling technique and demonstrate the clear spatial distribution of dissolved-phase hydrocarbons across the sampled area. If we compare our data with other study as illustrated in (Table 2) we can our study lies within these studies.

The Tukey HSD test provided a precise differentiation of TPH levels across the study area ($P < 0.05$). Station St1 was uniquely classified as the primary 'hotspot' (0.160 $\mu\text{g/L}$, Group a), reflecting maximum anthropogenic pressure from industrial and navigational activities. Stations St3, St5, and St2 followed as moderate-impact zones (0.135–0.107 $\mu\text{g/L}$), while St4 recorded the minimum baseline (0.096 $\mu\text{g/L}$, Group d). This rigorous grouping is our commitment to a truthful and transparent diagnostic; by identifying these specific 'pollution signatures,' we provide a clear, evidence-based guide for local conservation. Our goal is to ensure that environmental protection is targeted at the most vulnerable areas of the Shatt Al-Arab to safeguard the river's future for our community.

Table (1): Concentrations of Total Hydrocarbons in the Dissolved Phase $\mu\text{g/L}$.

Stations	Range	Mean	S.D.	S.E.
St.1	0.158-0.162	0.160 a	0.0020	0.0m012
St.2	0.105-0.109	0.107 cd	0.0020	0.0012
St.3	0.132-0.138	0.135 b	0.0030	0.0017
St.4	0.094-0.098	0.096 d	0.0020	0.0012
St.5	0.111-0.115	0.113 c	0.0020	0.0012

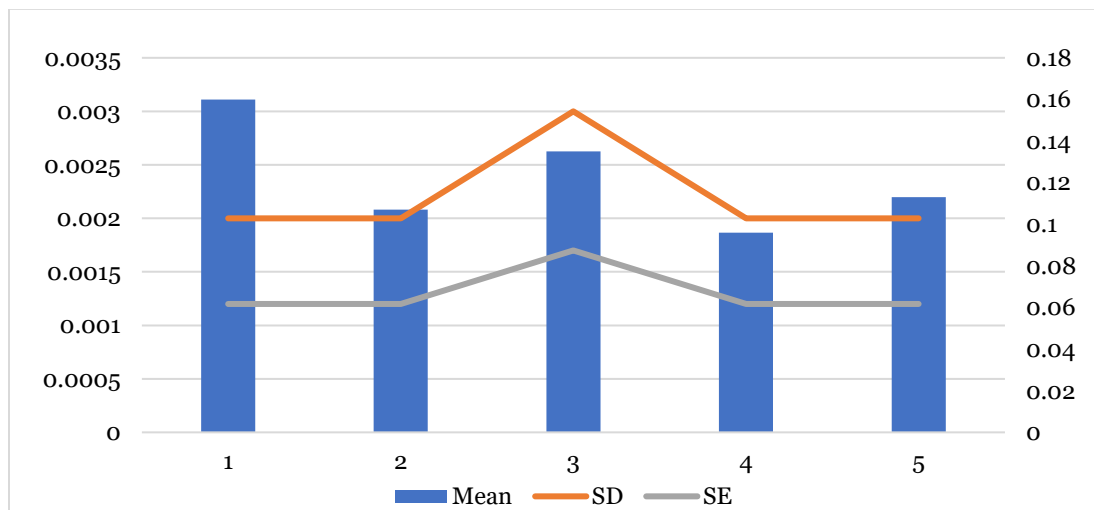


Figure (2): Variation of Total Hydrocarbon Concentrations in the Dissolved Phase $\mu\text{g/L}$.

Table(2): Summary of Previous Studies on Dissolved Total Hydrocarbons in Aquatic Environments

Position	THC in water ($\mu\text{g/l}$)	References
Shatt al-Arab	0.10–0.18	Al-Saad <i>et al.</i> , 2018
North Arabian Gulf	0.07–0.15	Al-Imarah <i>et al.</i> , 2019
Sao Sebasto coasts	2.5	Zanardi <i>et al.</i> , 1999
Victoria coastal	5.1 – 22.1	Burns & Smith, 1980
Chedabucto Bay	1.0-90.0	Levy,1979
Lyon Gulf	18.23	Marchand <i>et al.</i> , 1988
Malta Beach	14.9	Solnay,1979
Lybian Beach	24.9	Solnay, 1979
Saudi Arabia Beach	4.3 – 546	El-Samrah <i>et al.</i> , 1986
Qatari Beach	1.2 – 428	
Kuwaiti beach	2.1 – 3.6	
Shatt Al-Arab	5.2 – 14.2	Al-Saad, 1983
Shatt Al-Arab & NW Arabian Gulf	2.6 – 86.7	DouAbul, 1984
Shatt Al-Arab & NW Arabian Gulf	3.25 – 25.33	Al-Saad, 1995
Shatt Al-Basrah &Khor Al-Zubair	13.36	Al-Saadon, 2002
Shatt Al-Arab, Southern	3.97 – 11.72	Ibraheem, 2004
Iraqi coast	0.096-0.160	Current study

Suspended phase

The suspended phase serves as a key dynamic transport medium for the study area. The concentrations of hydrocarbons to illustrate this importance are illustrated in Table (3) with a maximum of 39.41 $\mu\text{g/g}$ at Station 3 (ST3), and a minimum of 15.22 $\mu\text{g/g}$ at Station 4 (ST4); the remaining stations measured as ST5, ST2 and ST1, exhibited medium to low values of hydrocarbons (28.09 $\mu\text{g/g}$, 23.85 $\mu\text{g/g}$ and 18.29 $\mu\text{g/g}$, respectively). This difference in hydrocarbons measured in a spatial manner is due to hydrodynamic conditions and sediment-water interactions as they relate to differing local areas.

Figure (3) illustrates hydrocarbons contained in the suspended phase and more effectively shows that the suspended hydrocarbons at ST3 come from remobilization of contaminated sediments at the bottom of the river (Al-Hajaj *et al.*, 2025). This is evidenced at ST3 where despite low hydrocarbons measured in the sediments, suspended hydrocarbons measured were very high; this has occurred due to water currents and turbulence flowing at ST3.

The much lower concentrations recorded at ST4 suggest a greater settling velocity of suspended particles, leading to a more rapid transfer of hydrocarbons from the water column to the sediment layer. This means that hydrocarbons are being deposited at a much faster rate into the sediments at this station than previously recorded, and it shows

how local hydrodynamics can control how permanently hydrocarbons are partitioned between suspended matter and bottom sediments (Hassan *et al.*, 2025).

The representative spike at Station 3 in Figure 3 illustrates the extreme level of activity associated with "resuspension" processes. Also illustrated in the graph of Figure 3, the hydrodynamic turbulence has played a significant role in remobilizing contaminants and turning the suspended phase into a primary dynamic transportation vehicle for residual oils. If we compare our data with other study as illustrated in (Table 4) we can see our study lies within other studies. The dynamic nature of the suspended phase is statistically validated by the exceptionally high variability reported in the ANOVA summary.

The F-value reached a remarkable 3813.57, which is the highest across all studied compartments. This statistical surge, vividly illustrated by the prominent spike at Station 3 in Figure 3, provides categorical evidence of active "resuspension" processes. and the visual representation in Figure 3 highlights the role of hydrodynamic turbulence in remobilizing pollutants, effectively turning the suspended phase into a primary dynamic carrier of oil residues.

The Tukey HSD test for the suspended phase revealed a significant shift in pollution hotspots compared to the dissolved phase ($P < 0.05$). Station St3 was uniquely identified as the primary 'hotspot' with a substantial mean of 39.41 $\mu\text{g/g}$ (Group a), followed by St5 (28.09 $\mu\text{g/g}$) and St2 (23.85 $\mu\text{g/g}$), while St4 remained the minimum baseline (15.22 $\mu\text{g/g}$). The high concentrations at St3 reflect the strong affinity of hydrocarbons for particulate matter in this specific sector of the Shatt Al-Arab (Garabedian, 2023).

This rigorous statistical grouping is our commitment to a transparent diagnostic; by pinpointing these particulate-bound 'priority zones,' we provide a truthful scientific guide to help local authorities target remediation efforts effectively, ensuring the long-term ecological health of the river for our community.

Table (3): Concentrations of Total Hydrocarbons in the Suspended Phase $\mu\text{g/g}$

St.	Range	Mean	$\pm\text{S.D.}$	$\pm\text{S.E.}$
St.1	18.10-18.48	18.29 d	0.190	0.110
St.2	23.60-24.10	23.85 c	0.250	0.144
St.3	39.00-39.82	39.41 a	0.410	0.237
St.4	15.05-15.39	15.22 e	0.170	0.098
St.5	27.85-28.33	28.09 b	0.240	0.138

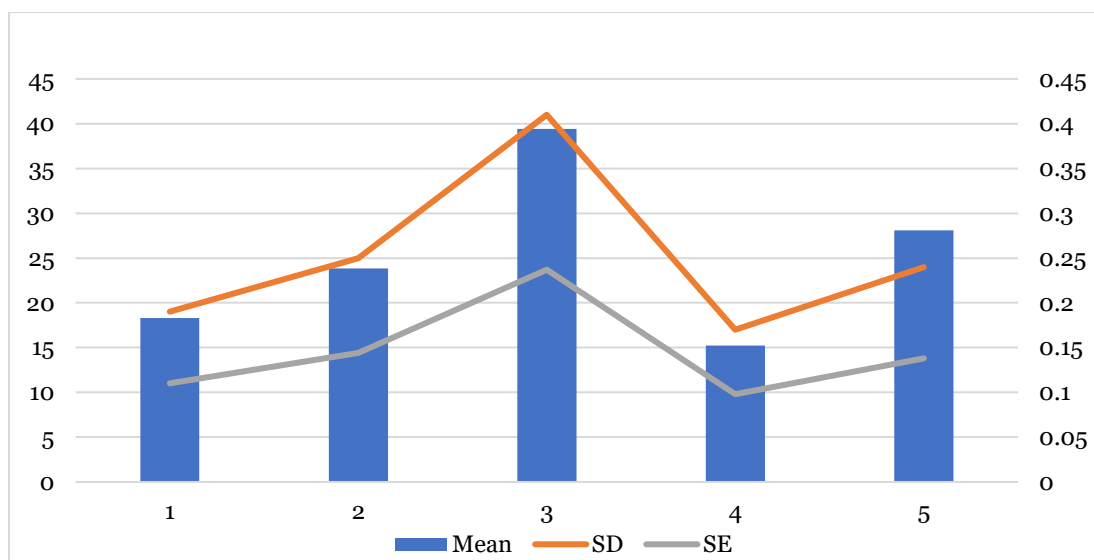


Figure (3): Variation of Total Hydrocarbon Concentrations in the Suspended Phase ug/g.

Table (4): Comparison study of particulate hydrocarbons with the Previous Studies on in the region

Region	Concentration (µg/g)	Reference
Shatt al-Arab	0.15–0.30	Al-Hejuje <i>et al.</i> , 2020
Arabian Gulf	0.10–0.25	Tolosa, 2016
Qatari beach	1.2–428	El-Samra <i>et al.</i> , 1986
Kuwait beach	2.1–3.6	
Antarctica	0.5–1.57	Bícego <i>et al.</i> , 2003
Baltic Sea	0.01–0.14	Pikkarainen and Lemponen, 2005
Khor Al-Zubair	36.8–478.2	Al-Saad <i>et al.</i> , 2006
Southern Iraq	0.012–0.037	Al-Saad <i>et al.</i> , 2009
Damietta Harbor, Egypt	14.5–65.5	Shereet, 2009
Niger Delta	19.3–27.9	Clinton <i>et al.</i> , 2009
Shatt Al-Arab river, Iraq	2.65–15.6	Al-Imarah <i>et al.</i> , 2010
The Gulf of Thailand	0.10–12.5	Wattayakorn, 2012
Brazil	0.0000344	Celino <i>et al.</i> , 2012
Khor Al-Zubair	8.92–153.57	Hashim, 2025
Iraqi coast	15.22–39.41	present study

Sediment Phase

Overall, sediments provide the greatest long-term storage of hydrocarbons than any other method Table 5 The highest mean concentration of hydrocarbons at Site ST1 was nearly double than in Site ST3 with Site ST1 measuring 92.41 $\mu\text{g/g}$ and Site ST3 measuring 46.13 $\mu\text{g/g}$ (the comparative numbers at ST4, ST2 and ST5 being lower but still consistent with decreasing amount of increasing distance from Site ST1). The spatial distribution of hydrocarbon concentrations represents the relative differences between the sources of these pollutants and their corresponding local environmental and depositional conditions (Sultan *et al.*, 2013). The hydrocarbon concentrations at ST1 and ST4 presented in Figure 4 indicate a substantial increase due to their proximity to industrial discharge sources and areas of high shipping traffic, resulting in the preferential transport of heavier fractions of hydrocarbons that are strongly retained within fine sediment particles along with their eventual permanent deposition (Al-Saad *et al.*, 2016). Conversely, the lower levels of hydrocarbons found at ST3 could represent a zone with a greater capacity for natural attenuation or local hydrodynamic conditions which limit stable sediment deposition, and consequently, prevent the long-term accumulation of hydrocarbons in this zone. By an analysis of variance (ANOVA), a strong statistical correlation has been established between sediments as final deposition areas for hydrocarbons showing evidence of significant long-term sediment accumulation gradients. Example data for Station 1 (ST1) and Station 4 (ST4) illustrate the accumulating hydrocarbon contaminants in both locations, as represented in Figure 4, by the dominantly short vertical bars at each sampling location will correlate with the results of the ANOVA analysis and demonstrate that both ST1 and ST4 are chronic retention sites for the sediment accumulation; thus indicating that these sediments will retain a large volume of hydrocarbon pollutants for many years and are part of what has been called "Environmental Memory". If we compare our data with other study as illustrated in (Table 6) its lies within these studies. The Tukey HSD test confirmed highly significant spatial variations in the sediment phase ($P < 0.05$), highlighting it as the primary sink for TPH accumulation. Station St1 was uniquely categorized as the most contaminated site (92.41 $\mu\text{g/g}$, Group a), showing a statistical dominance that reflects long-term industrial and navigational impact (Jazza, 2018). This was followed by St4 (Group b), while St3 recorded the lowest levels (46.13 $\mu\text{g/g}$, Group e). This precise statistical differentiation is our commitment to a transparent and honest diagnostic; by identifying these benthic 'priority zones,' we provide an undeniable scientific baseline to protect the river's bed and the aquatic life that depends on it, ensuring a healthier future for the Shatt Al-Arab.

Table (5): Concentrations of Total Hydrocarbons in Sediments ug/g.

St.	Range	Mean	$\pm\text{S.D.}$	$\pm\text{S.E.}$
St.1	91.50-93.32	92.41 a	0.910	0.525
St.2	67.80-68.70	68.25 c	0.450	0.260

St.3	45.90-46.36	46.13 e	0.230	0.133
St.4	73.10-74.74	73.92 b	0.820	0.473
St.5	53.85-54.47	54.16 d	0.310	0.179

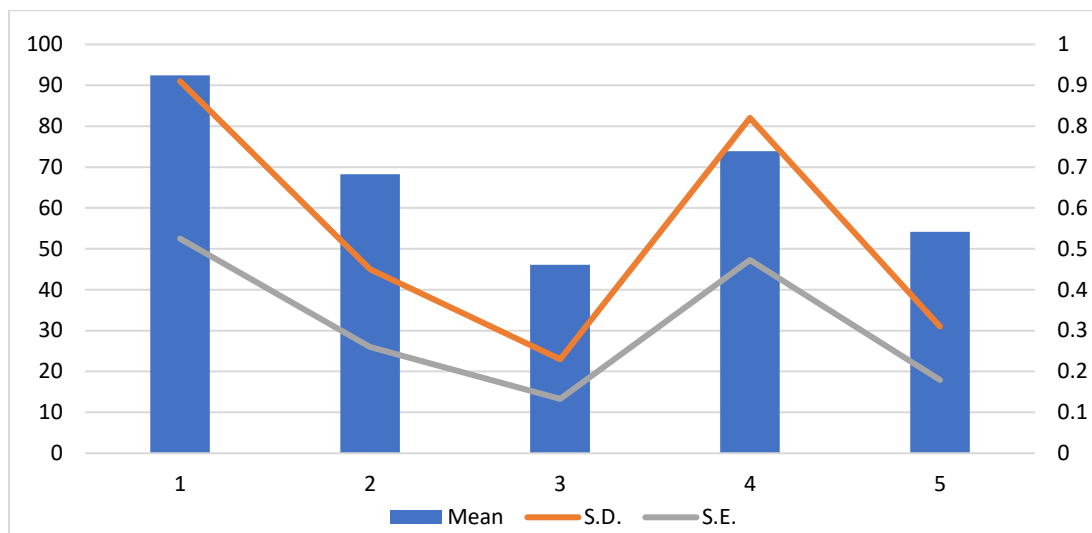


Figure (4): Variation of Total Hydrocarbon Concentrations in Sediment ug/g.

Table (6): comparison of Previous Studies on Total Hydrocarbon Concentrations in Sediments with other studies.

References	Conc. of TPHs (µg/g dry weight)	Locations
Al-Khatib, 2008	37.02-0.11	Al-Hawizeh Marsh
Al-Imarah <i>et al</i> , 2010	24.41-7.37	Shatt Al-Arab River – Northern Part
Jazza, 2015	135.18 - 3.16	Al-Kahla River – Missan
Al-Saad <i>et al</i> , 2017	49.09-19.43	Shatt Al-Arab Estuary and NW Arabian Gulf
Al-Atbee, 2018	17.98-2.98	Al-Chibayish Marsh – Thi Qar
Galo <i>et al</i> , 2022	5.57-6.98	Shatt Al-Basrah
Al-Hajaj <i>et al</i> , 2025	52.79-6.59	Shatt Al-Arab River
Al-Saad <i>et al</i> , 2016	20–5	Shatt al-Arab
Current study	46.13-92.41	Iraqi coast

Conclusions

While this research establishes a crucial spatial baseline for the Iraqi coastal environment, it is characterized by certain limitations. The study focused on a one-year temporal scope (2025), which may not fully capture the multi-seasonal fluctuations or long-term hydrocarbon dynamics. Furthermore, while ecological risks are inferred

through statistical grouping, direct toxicity and bioaccumulation tests were not conducted. Acknowledging these limitations is essential for future research, which should aim for long-term, multi-seasonal monitoring to provide a more comprehensive understanding of the Shatt Al-Arab's environmental resilience.

To conclude, this study provides ample evidence that the Shatt Al-Arab estuary and surrounding waters are chronically contaminated with petroleum hydrocarbons by long-term human influences as a result of anthropogenic activity, not just momentary pollution. The findings regarding the Total Hydrocarbon (THC) distribution among dissolved, suspended, and sedimentary phases in relation to the mechanisms of THC contamination suggest that there is an environmentally driven pathway for THC contamination based on the chemical and physical properties of hydrocarbons and the local hydrodynamic characteristics governing the transport of hydrophilic hydrocarbons from the water column into both suspended and bottom sediments. Although the concentration of dissolved THCs were found to be low, they indicate rapid movement of hydrophobic molecules from the water column into suspended particles in the water column and into bottom sediments. The suspended phase is considered to have acted as a constantly changing transport medium, when considering the relatively high concentration of THCs in the suspended phase as observed at station 3, where resuspension occurs more frequently. The sediment phase is identified as a much more significant long-term sink for hydrocarbons, with the highest concentration occurring at station 1 (industrial and maritime influences) and very low concentration at stations 2 and 4 (agricultural and aquacultural influences).

All compartments exhibited significant spatial variability ($P < 0.001$), which is further elucidated through an "Integrated Multi-Phase Interpretation": This statistical integration reveals a systematic partitioning pattern of hydrocarbons within the Shatt Al-Arab ecosystem. While the dissolved phase maintained the lowest concentrations due to low solubility, the significant increase in the suspended phase at St3 (39.41 $\mu\text{g/g}$) highlights the role of suspended matter as a transitional carrier. Ultimately, the sediment phase at St1 (92.41 $\mu\text{g/g}$) emerged as the final and most stable 'sink,' exhibiting the highest accumulation levels. This gradient from water to sediment, confirmed by Tukey's HSD groupings, reflects a continuous transfer of anthropogenic pollutants. This inter-phase relationship is not merely a chemical distribution but a clear indicator of long-term environmental stress, necessitating a holistic management approach to protect the river's benthic life and the human communities relying on its waters.

While this research establishes a vital spatial baseline for 2025, we acknowledge its specific one-year temporal scope. Therefore, these findings serve as a serious environmental warning, calling for the integration of ecological health assessments and multi-seasonal monitoring into future regional programs. Such steps are essential to ensure that the development of the Iraqi oil sector does not compromise the environmental security or the vital water resources of southern Iraq's communities, providing a more comprehensive understanding of hydrocarbon dynamics in response to

climatic fluctuations. In conclusion, our results confirm that the Shatt Al-Arab sediments serve as a permanent 'long-term sink' for petroleum hydrocarbons, acting as a persistent environmental stressor. This accumulation poses a significant risk of bioaccumulation and biomagnification within the aquatic food web, potentially jeopardizing fish safety and the health of local consumers. Moving beyond simple chemical monitoring, these findings serve as a serious environmental warning, calling for a balanced approach between industrial growth and the preservation of our region's ecological integrity.

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الهيدروكربونات البترولية الكلية في المياه الذائبة والعالقة والرواسب في مصب شط العرب والبيئة الساحلية العراقية

حيدر كاظم حيدر¹، صلاح مهدي صالح²، حامد طالب السعد²

¹قسم علوم البحار التطبيقية، كلية علوم البحار، جامعة البصرة، البصرة، العراق

²قسم علوم البحار الطبيعية، كلية علوم البحار، جامعة البصرة، البصرة، العراق

Corresponding Author E-mail: haider.kadimm@uobasrah.edu.iq

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المستخلص

يتضمن هذا البحث تحليلاً شاملاً لكيفية توزيع إجمالي الهيدروكربونات في مصب شط العرب والمياه الساحلية العراقية المجاورة في شمال غرب الخليج العربي خلال عام 2025. وقد تم تقييم كل من المكونات البيئية الثلاثة (الاجزاء الذائبة، والعالقة، والرواسب) بهدف دراسة تركيزات الهيدروكربونات فيها. وأظهرت النتائج وجود توزيع واضح ومنهجي للهيدروكربونات الكلية بين المكونات البيئية المدروسة. احتوت المكونات المذابة على تركيز منخفض نسبياً من الهيدروكربونات (من 0.096 إلى 0.160 ميكروغرام/لتر)، وهو نمط متوقع إلى حد ما نظراً لمحدودية ذوبان الهيدروكربونات البترولية وسرعة فقدانها من عمود الماء إلى الرواسب. في المقابل، عملت الجسيمات العالقة كوسيط نقل انتقالي بين الجزء الذائب ورواسب القاع، وتراوحت تركيزات الهيدروكربونات فيها من 39.41 ميكروغرام/غرام كحد أقصى (المحطة 3)، متأثرةً بعمليات إعادة التعليق والنشاط الهيدروديناميكي. تُعدّ رواسب القاع الموقع الرئيسي والأكثر استقراراً لترسب الهيدروكربونات، حيث تراوحت تركيزاتها بين 46.13 و 92.41 ميكروغرام/غرام، مع أعلى تراكم للهيدروكربونات في (المحطة 1)، مما يشير إلى استمرار وجودها بمرور الوقت وأنها ناتجة عن مصادر بشرية. أظهرت التحليلات الإحصائية، باستخدام تحليل التباين أحادي الاتجاه واختبار توكي HSD، تبايناً مكانياً ذا دلالة إحصائية ($p < 0.001$)، مما يُشير تحديداً إلى بؤر تلوث مكانية ذات مصادر محلية وخصائص رواسب مميزة. بشكل عام، سيوفر هذا البحث بيانات أساسية لمزيد من الدراسات، ويُبرز الحاجة إلى استراتيجيات متعددة القطاعات. نوصي بتقييم الصحة البيئية لرصد مخاطر التراكم الحيوي المحتملة، وذلك لضمان الأمن البيئي المستقبلي لشط العرب والمجتمعات التي تعتمد على موارده المائية.

الكلمات المفتاحية: إجمالي الهيدروكربونات البترولية، الذائب، العالق، الرواسب، مصب شط العرب، شمال غرب الخليج العربي .